A Methodology to Map Airport ASF's for Enhanced Loran

Richard Hartnett, US Coast Guard Academy
Kevin Bridges, Federal Aviation Administration
Gregory Johnson, Christian Oates, Michael Kuhn, Alion Science and Technology
Peter F. Swaszek, University of Rhode Island

BIOGRAPHIES

Richard Hartnett is Head of the Engineering Department at the U.S. Coast Guard Academy (USCGA). He graduated from USCGA with his BSEE in 1977, and earned his MSEE from Purdue in 1980, and his PhD in Electrical Engineering from University of Rhode Island in 1992. He holds the grade of Captain in the U. S. Coast Guard, and has served on USCGA's faculty since 1985. He is the 2004 winner of the International Loran Association Medal of Merit.

Gregory Johnson is a Senior Program Manger at Alion Science & Technology, JJMA Maritime Sector. He heads up the New London, CT office which provides research and engineering support to the Coast Guard Academy and R&D Center. He has a BSEE from the USCG Academy (1987) a MSEE from Northeastern University (1993) and a PhD in Electrical Engineering from the University of Rhode Island (2005). Dr. Johnson is a member of the Institute of Navigation, the International Loran Association, the Institute of Electrical and Electronics Engineers, and the Armed Forces Communications Electronics Association. He is also a Commander in the Coast Guard Reserves.

Peter F. Swaszek is a Professor of Electrical and Computer Engineering at the University of Rhode Island. He received his Ph.D. in Electrical Engineering from Princeton University. His research interests are in digital signal processing with a focus on digital communications and navigation systems.

ABSTRACT

In 2001, the Volpe National Transportation Systems Center completed an evaluation of GPS vulnerabilities and the potential impacts to transportation systems in the United States. One of the recommendations of this study was for the operation of backup system(s) to GPS; Loran-C was identified as one possible backup system. The Federal Aviation Administration (FAA) has been leading a team consisting of members from industry, government, and academia to evaluate the future of Loran-C in the United States. In a recently completed Navigation Transition Study, the FAA concluded that Loran-C, as an independent radionavigation system, is theoretically the best backup for the Global Positioning System (GPS). However, in order for Loran-C to be considered a viable back-up system to GPS, it must be able to meet the requirements for non-precision approaches (NPA's) for the aviation community, and the Harbor Entrance and Approach (HEA) requirements for the maritime community.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations are due to the signals propagating over paths of varying conductivity; these TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1x10^{-7}$.

The future of Loran for aviation is based on multi-station, multi-chain, all-in-view, DSP-based receivers observing TOA measurements with H-field antenna technology. For an aviation receiver, the approach to mitigate propagation issues under study is to use a single set of ASF values (one for each Loran tower) for a given airport. This value may have seasonal adjustments applied to it. The Loran receiver will use this set of static ASF values to improve position accuracy when conducting a non-precision approach (NPA). A Working Group is currently developing the procedures to be used to "map" the ASF values for an airport. The output of the Working Group will be a set of tested and documented procedures for conducting an airport survey; these procedures can then be followed to survey airports nationwide. This paper

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14. ABSTRACT

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discusses the procedures being envisioned and the testing methodology for the procedures. Equipment to be used in the surveys and the error budget for the survey equipment will be presented as well as a proposed error budget for the ASF methodology.

BACKGROUND / INTRODUCTION

Contrary to what some may believe Loran-C is still alive and in use worldwide. The United States is served by the North American Loran-C system made up of 29 stations organized into 10 chains (see Figure 1). Loran coverage is available worldwide as seen in Figure 2.

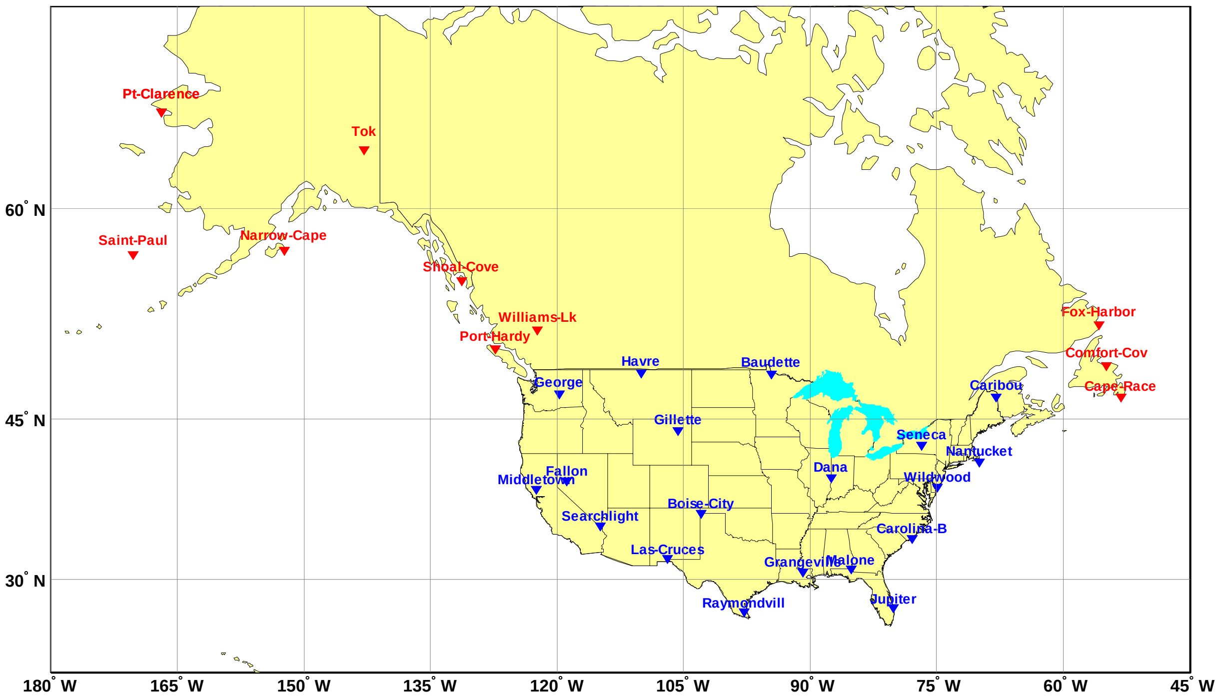

Figure 1 – North American Loran-C System, blue = new TFE stations.

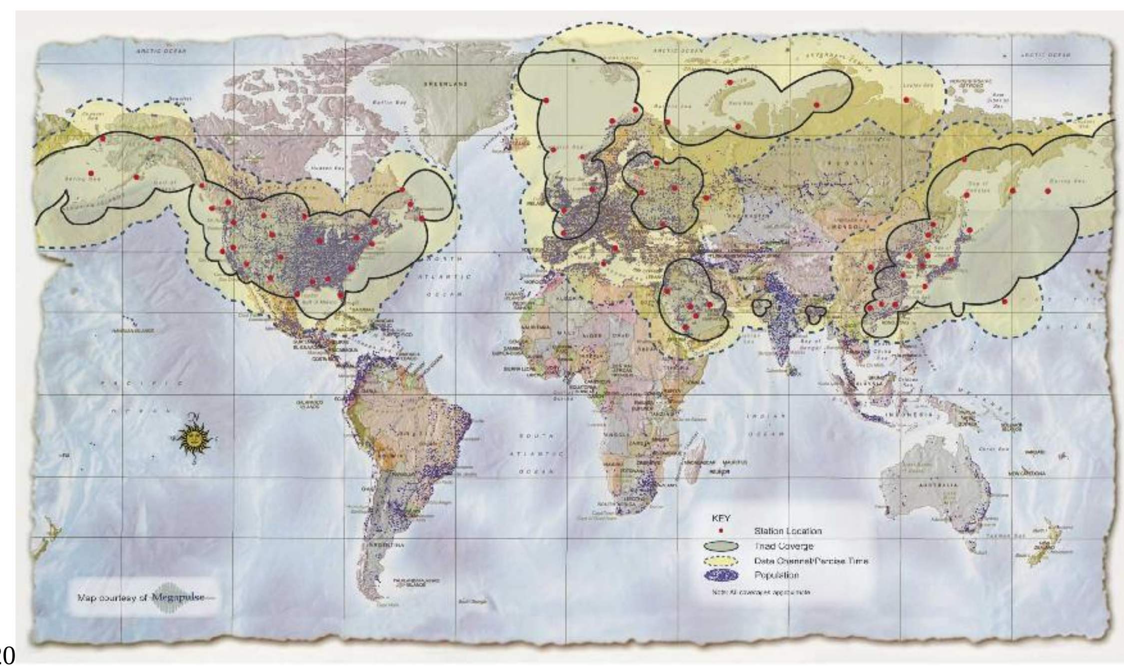

Figure 2 – Worldwide Loran Coverage

Given the ubiquity and quality of service available from the Global Positioning Service (GPS), one might wonder of what use is a system that has been operational since the 1970's? The answer is that Loran is an excellent backup system for GPS. As discussed in many sources, such as the Volpe vulnerability study [1], GPS is vulnerable to both intentional and unintentional jamming. Since Loran is a totally different system and subject to different failure modes than GPS, it can act as an independent backup system that functions when GPS does not. The Federal Aviation Administration (FAA) observed in its recently completed Navigation and Landing Transition Study [2] that Loran-C, as an independent radio navigation system, is theoretically the best backup for GPS; however, this study also observed that Loran-C's potential benefits hinge upon the level of position accuracy actually realized (as measured by the 2 drms error radius). For aviation applications this is the ability to support non-precision approach (NPA) at a Required Navigation Performance (RNP) of 0.3 which equates to a 2 drms position error of 307 meters and for marine applications this is the ability to support Harbor Entrance and Approach (HEA) with 8-20 m of accuracy.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations is due to the signals propagating over paths of varying conductivity; the TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1x10^{-7}$.

The future of Loran for aviation is based on a multi-station, multi-chain, all-in-view, DSP-based receiver observing TOA measurements with an H-field antenna. For an aviation receiver, the approach under study to mitigate propagation issues is to use a single set of ASF values (one for each Loran tower) for a given airport. If the local ASF variations are too large to meet the accuracy targets with a single set of ASF values, then additional sets will be used with the user receiver interpolating between ASF values. While ASFs also exhibit seasonal variation, our approach is to choose the ASF value for each station in the middle (median) of the seasonal range and to absorb the variation within the error budget. The Loran receiver will use this set of static ASF values to improve position accuracy when conducting a non-precision approach (NPA). The Loran Evaluation Panel Working Group on ASFs is currently developing the procedures to be used to "map" the ASF Correction Estimates (ACE) for an airport. The output of the Working Group will be a set of tested and documented procedures for conducting an airport survey; these procedures can then be followed to survey airports nationwide. This paper first discusses the proposed procedures and then a testing methodology that is envisioned to validate the procedures. Equipment to be used in the surveys and the error budget for the survey equipment is presented as well as a proposed error budget for the ASF methodology.

PROPOSED METHODOLOGY

Once an airport and its specific runways have been identified, the methodology consists of two parts:

1. computational and simulation work to establish locations for field tests

2. field measurements

Next we describe both of these components. Note that we have the working assumption that the BALOR ASF prediction software (described in [3]) provides a reasonable assessment of the real world conditions. One of the goals of the field measurement work of the working group is to validate this assumption.

METHODOLOGY PART I – COMPUTATION/SIMULATION

The first task in assessing the ASFs for a specific airport consists of identifying those Loran stations available for use in the position solution and to compute the predicted ASFs for the area using the BALOR software. BALOR is a software model developed by the University of Wales at Bangor and modified under an FAA-funded contract for the Loran Evaluation team. This software is designed for calculating predicted ASFs using the Monteath method [4-6]. It uses a terrain elevation database (DTED Level 1 format), a ground conductivity database (from the FCC), and a coastline database (World Vector Shorelines) for the ASF computations. The BALOR software computes ASF values on evenly spaced grid points; for our analysis and simulations we computed these values for a grid spacing of 0.001 degrees both in latitude and longitude. Additional details on our use of the software are contained in [7, 8].

The primary goal of computing the ASF grids is to determine whether one set of ASFs is sufficient for each approach path or if multiple sets are needed. This is accomplished by considering the worst case ASF differences, the station geometries, and the expected signal to noise ratios. Since this only takes into account predicted ASFs, not model errors and other noise sources, we also simulate the position solution for comparison to

the maximum desired value of 120 meters[1]. To simulate time of arrival (TOA) data using these grids, for a specific latitude/longitude position we generate the TOA as:

$$TOA_{sim} = TOA_{pred} + ASF_{pred} + E_{delay} + Noise$$

Here, TOA_{pred} is the predicted arrival time given the precise distance from the corresponding Loran tower to the desired location based on an all-seawater propagation path, ASF_{pred} is the bilinear interpolation of the BALOR ASF grid at that location, E_{delay} is the published emission delay for the station relative to the Master, and Noise combines all potential noise sources. For the aviation simulation, we model three noise sources:

- Directional variation due to antenna issues – a typical one sigma (standard deviation) value is 100 nsec.
- Altitude variation due to differences in ASF values (BALOR computes at fixed AGL) – currently we are using 100 nsec as the one sigma value.
- Receiver channel noise – in the range of 25-100 nsec depending upon the station SNR.

This examination of the worst case effects of ASF differences focuses on the approach paths for each runway (out to 10 miles from the runway end); the simulation examines a subset of points along the approach focusing on potential bad spots due to ASF differences.

A final step in this analysis would be to re-examine performance under the loss of some of the Loran stations.

AN EXAMPLE

As an example, we consider Walker Field in Grand Junction, CO. This airport has 4 runways (IDs 11, 29, 4, and 22) in an L shape. Extending the approaches out 10 miles, we are interested in the BALOR predictions for Latitudes 39.005 to 39.238 North and Longitudes –108.329 to –108.730 West. Figure 3 depicts this bounding box showing the runway as solid black, the approach paths in dotted blue, and potential simulation points as +'s. For a Loran solution, we consider four stations within 1000 km: Boise City, Gillette, Searchlight, and Las Cruces. Figure 4 shows the relative locations of Grand Junction and these Loran towers.

[1] Although the accuracy constraint to meet RNP 0.3 is 307m, due to other error components such as seasonal variation and transmitter noise, the position domain bound has been set at 120m for spatial error.

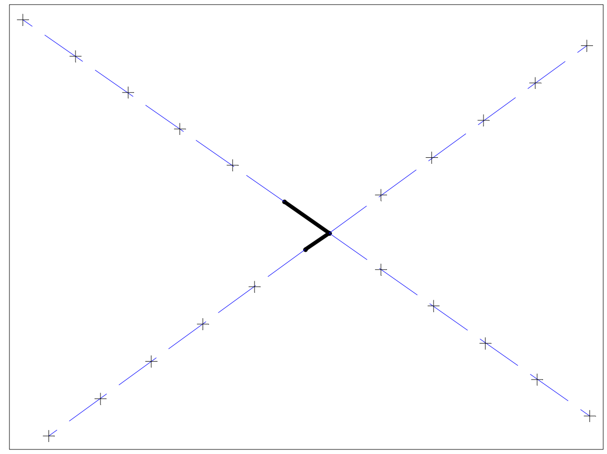

Figure 3 – Walker Field runways and approach pattern.

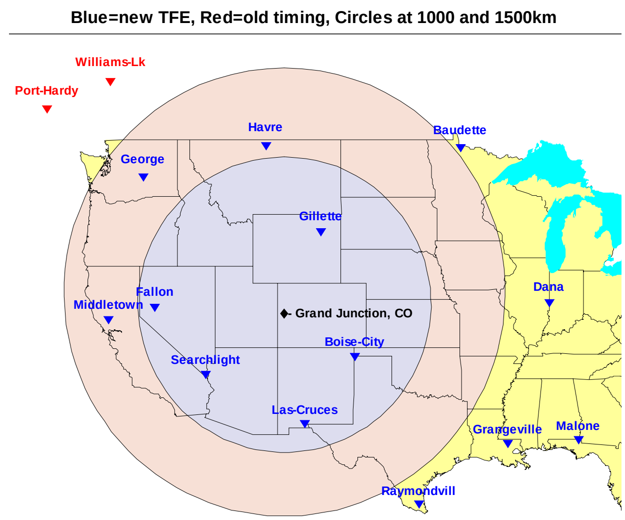

Figure 4 – Loran towers around Grand Junction. Circles at 1000 and 15000 km.

Next we employ BALOR to estimate the ASFs for these stations; Figures 5 and 6 show these for Gillette and Boise City, respectively (the approaches are overlaid on these contour plots for convenience).

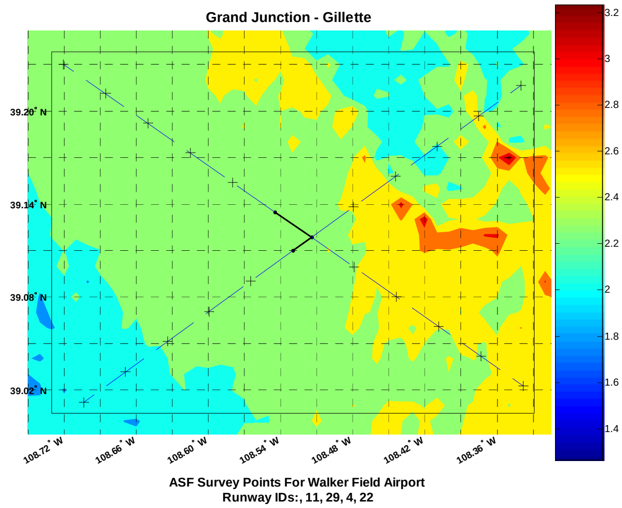

Figure 5 – BALOR for Gillette about Grand Junction.

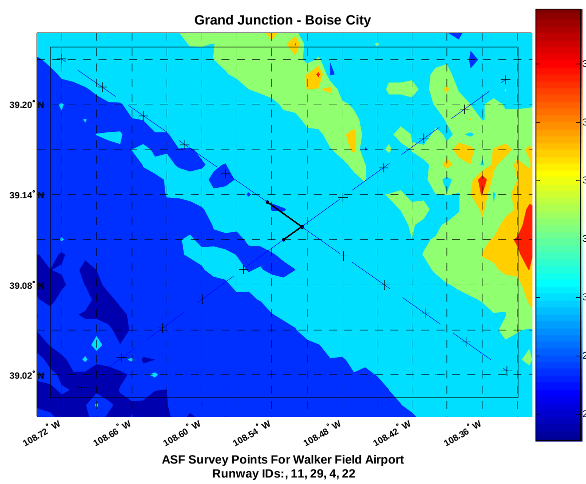

Figure 6 – BALOR for Boise City about Grand Junction.

Of more interest are the predictions along the approaches. For this example, we concentrate on runway 29 (the lower right of Figure 3) and show in Figure 7 the ASF predictions for each of the four Loran stations. The dotted lines correspond to the value at the runway end – the value that would typically be employed as the single ASF for navigating.

While the actual values of the ASFs are interesting, any common value is absorbed into the clock offset solution and the performance is only impacted by the ASF differences. These are shown in Figure 8. Note the worst case difference of 237 nsec at approx 16 km out.

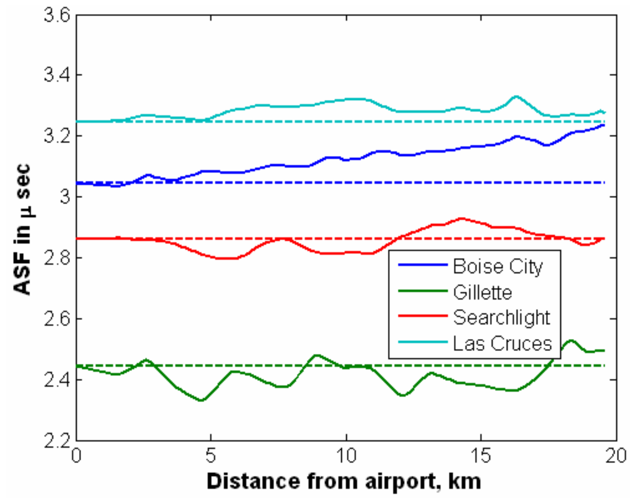

Figure 7 – BALOR along the approach for runway 29.

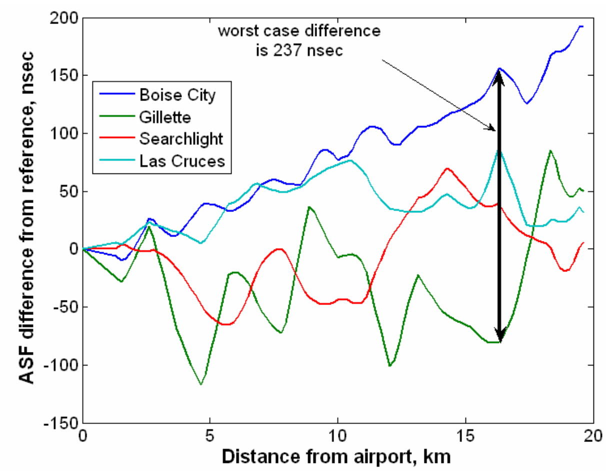

Figure 8 – BALOR differences along the approach for runway 29.

With these ASF predictions we can compute the effect of the ASF mismatch on position solutions for a user implementing ASF correction using the ACE value. Specifically, we predict the TOA from:

$$TOA_{expected} = TOA_{pred} + ASF_{pred} + E_{delay}$$

(the only difference from the simulation TOAs is the lack of noise). We then subtract out the ASF estimate, ACE,

$$TOA_{adjusted} = TOA_{pred} + ASF_{pred} + E_{delay} - ACE$$

and compute the position using these values. Figure 9 shows, as the blue line, the performance of this approach as horizontal error due to the ASF mismatch and the underlying Loran geometry (the HDOP). We note that the largest error corresponds to the largest ASF difference at approximately 16 km out. We note that the ASF mismatch of one set of ACE values is in the range of 20-40 meters for most of the approach. To simulate this situation, we select a set of 10 points evenly spaced along the approach

path, plus the runway end itself. These sites are shown for all four approach paths to Walker Field in Figure 10. Of particular interest in this example are the two points marked by circles for runway 29: the runway end itself (which has zero ASF mismatch) and the point approximately 16 km out with maximum ASF difference.

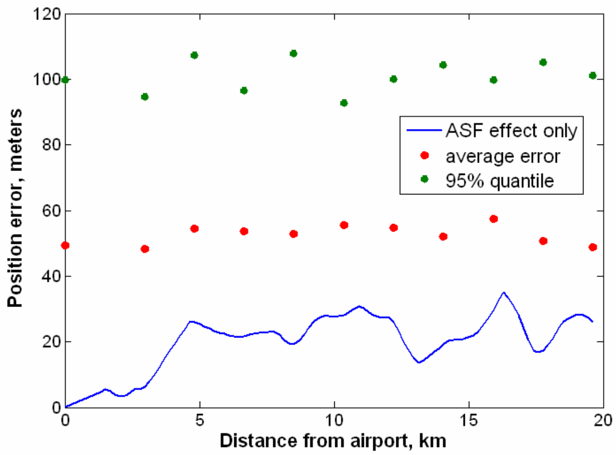

Figure 9 – Position performance along approach to runway 29.

Adding the noise sources and other unknown variations (directional, temporal, and receiver noise) as per the simulation equation above, typical performance results are overlayed on Figure 9 of the theoretical performance. The red dots show the average horizontal error for 10 points uniformly spaced along the approach plus the point at the runway (distance 0); the green dots show the 95% range. We note that across this entire approach, the error is dominated by the error terms, not the ASF mismatch, with average of about 50 meters and 95% quantile of approximately 100 meters.

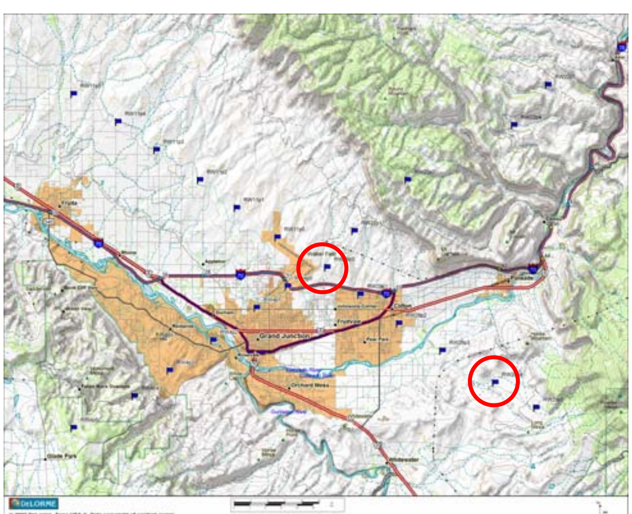

Figure 10 – Test sites for Walker Field.

This example satisfies our RNP 0.3 restriction of horizontal error less than 120 meters using the four Loran stations available. To continue this example, we would examine for theoretical and simulation performance under all subsets of the potential Loran stations. If the simulations exceeded the 120 meter limit, the secondary goal of the analysis would be to determine how many and where additional ASF values would be identified and/or which Loran stations are critical to system performance.

METHODOLOGY PART II – FIELD TESTS

The purpose of this second part is to validate the analysis above by measurements in the field. To remove temporal variations in ASFs, either due to system errors or selected environmental effects (e.g. weather, season), a static monitor is set up at the airport collecting TOAs for all Loran stations of interest during the entire test period. A second TOA measurement system is employed to measure TOAs at the selected test sites along the approaches. The airport TOAs and any system timing offsets (available in data captured at the Loran stations) will be subtracted from these test site TOAs to remove any temporal variation; the residual is a combination of the spatial ASF and noise. We have several notes:

- The desired test site locations may not be reachable (no roads, private property, etc.). We expect to be able to reach points to within 0.5 miles crosstrack from the approach centerline and 0.5 miles along the approach path itself.

- Sufficient data must be collected at each test site to average out noise effects to achieve an ASF measurement accuracy of a standard deviation of 25 nsec. or less. This collection time is a function of the station rate, the received SNR, and must recognize that the differencing of TOAs with the static monitor doubles the effective receiver noise (hence, 4 times as many samples are required).

Once the measurements are completed, ASF correction estimates (ACE) for each airport (or for each runway at an airport if necessary) will be assigned. These ACE values will also be adjusted to the center of the seasonal range for the area so that a single set of values is valid for the entire year.

VALIDATING THE METHODOLOGY

During the summer of 2005, a USCGA/Alion/FAATC team will be conducting ASF measurement tests to validate the proposed methodology. Its two goals are to assess BALOR’s ability to accurately model the ASF variation and to evaluate the methodology proposed above. The methodology will be modified as necessary based upon the results of these tests.

The test has several components, described in the following sections: Ground Measurements, Flight Verifications of RNP 0.3, Long Baseline Measurements, and ASF Profile vs. Altitude.

GROUND MEASUREMENTS

Ground measurements will be conducted at several airports (in New Jersey, Maine, and Ohio) consisting of both the static airport monitor and the measurements at a variety of test points along the airport approaches. In this trial, more points (one every 1-2 miles) than expected to be necessary for a typical airport will be measured to provide more data to assess the validity of the BALOR predictions. The data collection system is mounted in a van with mast antenna as shown in Figure 11. The variance of the data will be monitored to ensure that sufficient data points are taken to yield the desired accuracy. In addition, a second static monitor will be employed to test the spatial correlation of the temporal effects.

Figure 11 – The test van.

The average ASF* (ASF plus noise terms) will be calculated for each test point. The true ASF for each test point will be calculated by correcting the ASF* for the temporal variance using the static monitor and for system time errors using the Time and Frequency Equipment (TFE) data from the Loran stations.

FLIGHT VERIFICATION OF RNP 0.3

In order to verify that the assigned ACE values work, a series of flight verifications will be conducted on each runway. Multiple approaches to each runway will be conducted (5 per runway) to collect TOAs in flight using the FAATC Convair 580 as shown in Figure 12. In a post-process mode, the measured TOAs will be corrected using the ACE value for the airport and the position accuracy measured for each point along the approach path. In addition, the ASF values will be calculated (as described above) for each point along the approach path for another comparison to the BALOR predictions.

Figure 12 – The test plane.

LONG BASELINE MEASUREMENTS

Long baseline measurements (in-flight TOA data) will be collected along flight paths to/from selected Loran towers to assess BALOR accuracy at large scale (> 1000 km) prediction of ASFs. Flight paths that will provide a variety of propagation paths to/from the Loran towers: all-seawater, all-land, and mixed seawater and land, are planned. We are planning to fly radials (at 5000 ft AGL) to/from the towers so as to keep the propagation paths fixed. Data will be collected using both E and H field antennas. Post-processing will include the computation of ASFs along the radial paths (subtracting out system timing information from the station TFE as before) and comparison of the measured ASFs and signal strengths to BALOR predictions.

ASF PROFILE VERSUS ALTITUDE

The BALOR predictions are only accurate for ground level; however, previous tests have indicated that there is some change in ASF with altitude. For example, see Figure 13 which shows some ASF data measured using the Convair 580 near Atlantic City NJ. ASFs are plotted vs. Latitude for a variety of altitudes and show some definite differences. However, all previous efforts at investigating this have been done using an aircraft which is not an accurate ASF measurement platform due to the speed of motion and noise, so we have not been able to draw definitive conclusions.

In order to resolve this issue, one component of the summer testing will be to use an airship as shown in Figure 14 in an attempt to bound the variation in ASF with altitude. For RNP 0.3, 4000 feet AGL is the maximum altitude of interest (the maximum altitude for starting an airport approach). The plan is for the airship to hold its position at 1000 ft altitude increments (over a static latitude/longitude), collecting both E and H field antenna TOAs. Differencing the collected data from a static monitor at ground level and correcting for system time errors using TFE data will provide an ASF profile versus altitude. Weather information at the site and along the propagation paths will be collected for archival value.

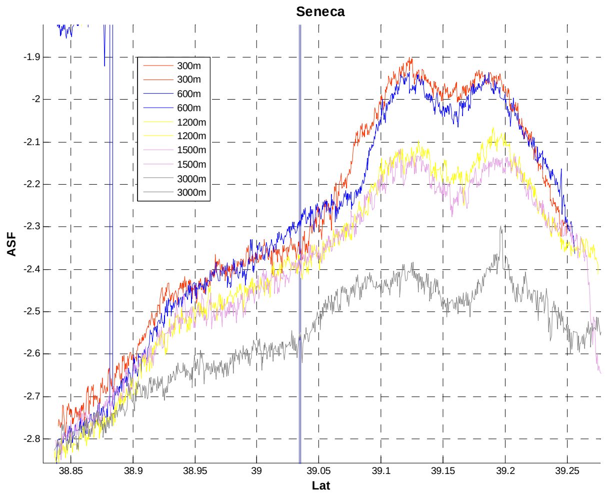

Figure 13 – Seneca ASFs vs. Latitude for altitudes of 300-2000m

Figure 14 – The airship.

FIELD TEST EQUIPMENT

The equipment setup for this field testing is shown in Figure 15 in block diagram form. It consists of both E and H field Loran receivers for measuring TOAs. A rubidium clock is used to provide a common, stable, 10MHz reference to all equipment. A L1/L2 GPS receiver is used to provide a reference position track and a 1PPS synchronized to UTC for timing measurements and to provide long-term stability to the rubidium clock. Digital counters are used to measure the time difference between the PCI strobes from the Loran receivers and the UTC 1PPS to enable the ASF calculations. Not shown is the weather station to collect environmental data. All data is collected on a laptop running Alion's RcvrIntegration software.

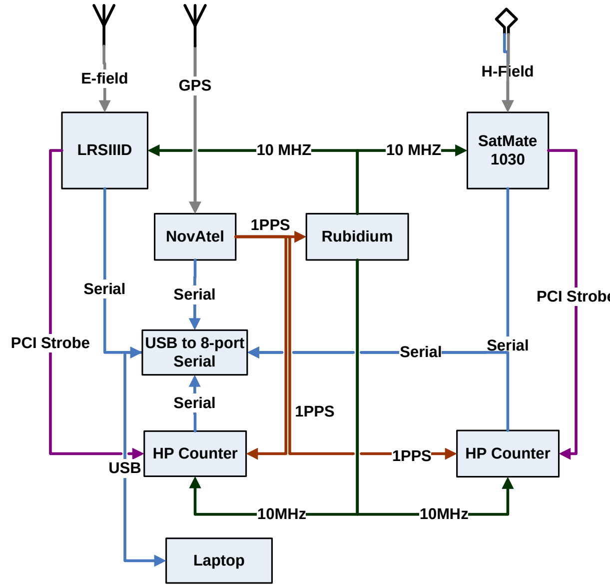

Figure 15 – Field test equipment.

An important consideration for the testing is knowing the accuracy of the measurements. Each piece of equipment has been tested to measure the error. A table showing the signals of interest and their accuracies appears below.

Tab1e 1 – Equipment Accuracy

Item	Error	Device
10 MHz Stability	1.312e-12	Rubidium Clk
1 PPS Stability	Mean = 0ns σ = 2.2ns	NovAtel GPS
1 PPS offset from UTC	TBD	NovAtel GPS
RF Gate Stability	Mean = 0ns σ = 0.698ns	LRSIIID
PCI Strobe Stability	Mean = 0.5ns σ = 2.102ns	SatMate 1030
Counter Resolution	150 ps	Agilent Counter
TOA Stability	10-20ns, SNR dependent	LRSIIID and SatMate

CONCLUSIONS/FUTURE WORK

At this time our test equipment is assembled and tested, the test plan described above is complete, and field testing has begun (currently, June 2005, tests are occurring at the FAA Technical Center in New Jersey). During July 2005

we will be field testing in Maine, with a trip to Ohio scheduled for August 2005. The long baseline flights are scheduled for Sept 2005; the airship altitude test schedule is awaiting a window of opportunity based upon the schedule of the commercial airship under consideration. We will be describing the results of the field testing and Methodology validation at a future ION conference.

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DISCLAIMER AND NOTE